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Cold Regions Research and Engineering Laboratory

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Laboratory Evaluation of Expedient Low-Temperature Concrete Admixtures for Repairing Blast Holes in Cold Weather

Jared I. Oren, Edel R. Cortez, and Charles E. Smith, Jr.

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US Army Engineer Research and Development Center
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Final report

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Abstract

Previous research has demonstrated the efficacy of various commercial admixtures for rapid setting concrete in cold weather environments, but this research has mostly focused on gathering data on too large a time window (more than 7 days) and focuses on admixtures largely unavailable in Afghanistan. The research included in this report investigates admixtures which can satisfy the Army operational requirement. These requirements include 45–90 minutes of concrete workability, followed by a rapid-strength gain to the point of being "undiggable," and the ability to support anticipated vehicle loads within 3 to 5 total hours from first contact of water to binder material. This research ignores typical concerns such as long-term durability, aesthetics, corrosion, and others that are of minimal importance in this expedient field use application—concrete not expected to last more than 5 years. Results from this study were incorporated into Army guidance addressing the use of rapid setting materials for crater repair. This report describes the repair methods and early strength gain performance (as measured by penetration resistance) of the rapid setting materials used in laboratory tests to repair small-to-large craters at ambient temperatures (about −10 to 0°C). An appendix then combines this research and existing knowledge of admixture use at temperatures above 0°C to provide non-technical, expedient instructions for Soldiers' tactical hasty road repair in a broad range of low temperatures using locally procurable (in Afghanistan) materials.

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Preface

This is a Technical Report in response to US Army Corps of Engineers Reachback Operations Center (UROC) RFI-2012-3016-AFG-N-Cold Weather Concrete Mixture Testing.

The work was performed by Jared I. Oren and Dr. Edel R. Cortez (Force Projection and Sustainment Branch) and Charles E. Smith, Jr. (Engineering Resources Branch, Wallace Celtrick, Chief), US Army Engineer Research and Development Center/Cold Regions Research and Engineering Laboratory (ERDC/CRREL). At the time of publication, Dr. Justin Berman was Chief of the Research and Engineering Division. The Deputy Director of ERDC/CRREL was Dr. Lance Hansen and the Director was Dr. Robert Davis.

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COL Kevin J. Wilson was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
yards	0.9144	meters

Executive Summary

This report was developed in response to inquiries from several operational combat and construction engineer units operating in Afghanistan, compiled and formally addressed through the US Army Corps of Engineers Reachback Operations Center (UROC). All inquiries were related to the following general question: How can combat and construction engineers conduct expedient blast (IED) hole repair in Afghanistan at low temperatures with locally procurable materials using existing, basic mixing equipment? The ability to repair blast holes during the fall, winter, and early spring months is critical to maintaining maneuverability in all seasons, and there is great incentive to do this in the colder months owing to the seasonal drop in insurgent activity.

This report is composed of several stand-alone documents to be used for varying purposes: Sections 1–7—a technical analysis and write-up of all new laboratory research conducted to understand concrete materials and procedures necessary to performing hasty crater repair at −10 to 0°C (14 to 32°F); Appendix A—all laboratory data for mortar and concrete testing at −10 to 0°C; and Appendix B—a *Hasty Road Repair Soldier's Expedient Guide*, which combines this research and existing knowledge of admixture use at temperatures above 0°C to provide non-technical, expedient instructions for Soldiers' tactical hasty road repair at a broad range of low temperatures, using locally procurable (in Afghanistan) materials. In addition, a separate attachment was created in Excel, *Hasty Crater Repair Calculator*, which supplements Appendix B and should be used during the planning and execution stages for any hasty crater repair operations by engineer units. A screenshot of this easy-to-use tool is included in Appendix B.

It is recommended that Appendix B and the calculator tool be disseminated to the Maneuver Support Center of Excellence (MSCoE) at Ft. Leonard Wood, MO, and incorporated into the Engineer Branch's concrete and assured mobility academic curricula.

Follow-on field testing using both the Concrete Mobile Mixer (CMM) and small, portable cement mixers by Soldiers is desired to further improve the

practicality and implementation of the instructions enclosed in the Soldier's Expedient Guide.

1 Introduction

1.1 Background

In conflict areas in Afghanistan, insurgents are using existing blast holes to plant new Improvised Explosive Devices (IEDs) to target coalition convoys. An effective solution to this problem is to repair the blast holes with Portland cement concrete (PCC) materials. During the winter season, insurgent activity diminishes because of cold weather and typically resumes in a spring offensive. It would be desirable to continue the repair of existing blast holes during the winter season to improve security conditions for coalition military convoys maneuvering during the spring offensive. However, normal PCC does not set fast enough in cold environments, and freezing of fresh concrete may permanently damage the PCC material, rendering it ineffective.

Previous research at CRREL has demonstrated the efficacy of various commercial admixtures for rapid setting concrete in cold weather environments (Korhonen and Brook 1996; Korhonen et al. 1997a; Korhonen et al.1997b). Various experiments with reagent-grade chemical compounds led to the use of combinations of commercial admixtures for cold weather concrete to satisfy three required characteristics. First, one type of admixture was necessary to depress the freezing point of water, ensuring sufficient available water to undergo hydration with the Portland cement. Next, the same or another type of admixture was typically necessary as a “catalyst” to accelerate the rate of hydration. Finally, a third admixture was usually necessary to act as an initial retardant, allowing for initial concrete workability and preventing flash setting. However, this previous research has mostly focused on too large a time window (more than 7 days) with little analysis quantifying performance under 12 hours.

Our research investigates admixtures that can satisfy the Army operational requirement. These requirements include 45–90 minutes of concrete workable time, followed by a rapid-strength gain to the point of being “undiggable,” and the ability to support anticipated vehicle loads within 3 to 5 total hours from first contact of water to binder material. This research ignores effects on long-term durability, trafficability, temperature rebar corrosion, and other concerns that are of minimal importance in this expedient field use application—concrete not expected to last more than 5

years. This report describes the repair methods and early strength gain performance (as measured by penetration resistance) of the rapid setting materials used in a laboratory test to repair small to large craters.

The solutions presented reduce the required on-site time for Soldiers conducting hasty blast hole repair, and for on-site security, from days currently (depending on temperature and other factors) to approximately 3–5 hours, which is the total amount time required for the cold weather concrete to harden and set to the point of being undiggable. This period begins when water is first added to the cement.

The solutions hereby provided are to be used only for the stated purpose: expedient filling of blast holes in forward military areas where low temperatures are a concern (high altitude, winter, or other expectation of near or below-freezing weather). These solutions are not intended for civilian construction because the material produced may not meet the required quality, durability, and appearance normally required by most architectural and structural applications. For such applications, contact the author for more appropriate solutions.

1.2 Project description

In response to a request for information (RFI) from an engineer unit in Afghanistan, processed by the US Army Corps of Engineers Reachback Operations Center (UROC), the US Army Engineer Research and Development Center (ERDC) tested and evaluated alternative admixtures to rapidly repair small to large blast holes in Afghanistan during cold weather. This investigation, owing to time and budget constraints (30 day window), surveyed and down-selected for further laboratory testing from the most promising materials with rapid 7-day strength gain outlined in previous expedient admixtures research (Korhonen 1999). Laboratory testing focused on the search for admixture combinations that would allow PCC to resist freezing during initial curing, to accelerate the rate of hydration, to maintain workability for 45–90 minutes and still set from 3 to 5 hours after water addition, and to provide stable results through a variety of variables, including temperature (−10 to 0°C), admixture proportions, water to cement (w/c) ratios, and other factors. For expediency, all admixtures were tested for suitability using mortar mixes using primarily an ASTM penetration resistance procedure (ASTM C403 2008), with the best performing combination ultimately tested with a concrete mix and a similar

penetration resistance test. All laboratory tests were conducted at the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH.

1.3 Project objectives

The objectives of the project were to

1. identify, through laboratory testing, the most promising admixture combination for rapid concrete setting in ambient temperature ranges of −10 to 0°C.
2. use admixtures available through the Army supply system in Afghanistan (existing supplies in area of operations or accessible via local purchase).
3. provide an empirical procedure for determining concrete setting time to an "undiggable" hardness and strength using Army universal tools or equipment.
4. minimize the variability of results caused by variables difficult to control in the expected environment, to include temperature (ambient, materials), admixture dosage, concrete component proportions, water-cement ratio, and mixing equipment and methods used.
5. provide guidance for the use of admixtures to rapidly repair blast holes and restore maneuverability within 3 to 5 hours without a significant manual excavation and re-emplacement threat.

1.4 Project scope

This project was limited to the identification of one "most promising" admixture combination to fit the above objectives from an array of previously identified admixtures. Given the time and budget constraints, to fulfill the RFI, we ignored various considerations, such as product variation or more thorough design of experiment analyses to produce a general model (see recommendations).

2 Technical Approach

2.1 Introduction

The desired end state of the laboratory testing was to determine a combination of admixtures that work together to provide suitable rapid setting times (3–5 hours) and an initial workable time period (45–90 min) in temperature ranges of −10 to 0°C. Previous studies detailed the primary effect of each admixture chosen in this study as a hydration rate accelerator, freezing-point depressant, or retarder (Korhonen 1999). Additionally, previous studies have shown the necessity of using a combination of admixtures to achieve a longer and more stable concrete workability period followed by a rapid strength increase at low temperatures (−15 to 0°C). However, the key information omitted from the research was the early strength gain (within 5 hours of first water addition to cement) for various admixture combinations (see, for example, Korhonen 1999; Korhonen et al. 2004). Finally, previous studies have demonstrated the efficacy of using mortar samples as a proxy for concrete testing when investigating admixtures for a variety of uses to accelerate the laboratory testing pace. This works provided that results for all mortar tests are correlated and mapped to concrete tests (Korhonen 1999). Therefore, to reduce the computational complexity in determining, with varying quantities of proposed admixtures, how to achieve these three opposing effects to satisfy the problem constraints, the laboratory testing followed three distinct phases: a single admixture scanning mortar phase, an admixture combination effects mortar phase, and a results verification concrete test. Additionally, the following variables were fixed throughout the laboratory testing to conform to materials availability in Afghanistan, to reduce computational complexity, and to simplify procedures for the end user: concrete primary materials (Type I Portland cement, concrete sand, ¾ -in. crushed aggregate), concrete materials ratio by weight (1:2:3, cement:sand:aggregate), and admixture brands.

The goals of the single admixture scanning phase were the following:

1. Verify each admixture’s effects versus Type I Portland cement on time of set at −5°C.
2. Determine minimum admixture proportions (added by proportion of weight of cement) necessary to exhibit each admixture’s primary effect

(freezing point depression less than −5°C, retarding effect, or hydration rate acceleration).

3. Determine the effect of individual admixtures on workability given a fixed water-cement ratio (0.36) and temperature (−5°C).
4. Predict which admixtures will work best in combination to provide three simultaneous properties (freezing point depression less than −5°C, retarding effect, or hydration rate acceleration) to meet the specified time of set requirements.

The goals of the admixture combination effects phase were the following:

1. Verify that the candidate admixture combinations provide the three simultaneous properties when mixed together with no major unintended effects.
2. Determine the proportions of the candidate admixture combinations necessary to provide the three simultaneous properties to meet the specified time of set requirements, given a fixed water-cement ratio.
3. Determine the effect of water-cement ratio variation on the results in 2 above to recommend an optimal water-cement ratio.
4. Determine the effect of temperature (−10 to 0°C) on the results in 2 above.
5. Determine an empirical procedure for associating mortar diggability with measured penetration resistance (ASTM C403 2008).

The goals of the results verification concrete test were the following:

1. Verify the admixture proportions required to provide the three simultaneous properties to meet the specified time of set requirements with the introduction of large aggregate.
2. Verify that the recommended water-cement ratio allows for sufficient mixing and workability.
3. Verify the empirical procedure results for associating concrete diggability with measured penetration resistance.

We tested samples of each mix in varying quantities per variable introduced (temperature, admixture type, admixture proportions, water-cement ratio), depending on the phase of testing.

2.2 Materials

This study used mortar as a rapid way to evaluate various chemicals in the first two phases. Previous studies involving cold-weather admixture testing have demonstrated the suitability of using mortar. Mortar simplifies mixing operations, reduces material handling, and permits smaller test specimens. However, it still closely simulates concrete results as mortar has the same paste to aggregate transition zones, albeit smaller (Korhonen 1999; Korhonen et al. 1997a, b). The mortar was non-air-entrained, used Type I Portland cement at 1:2 ratio with sand, and was made with water-cement ratios between 0.36 and 0.45 (the majority of the testing was at 0.39–0.40 w/c). The sand, sieved for use in concrete, had a bulk specific gravity (saturated surface-dry) of 2.70 and a moisture absorption of 1.0%. The mixing water was from the taps at CRREL.

See Table 1 for admixtures used.

Table 1. Commercial admixtures used in laboratory testing.

Admixture	Notes
Calcium chloride deicing pellets	
Calcium nitrate fertilizer	15.5% Nitrogen (14.5% - Nitrate, 1% - Ammonium), 19% Calcium.
Sodium nitrate fertilizer	“Chile Saltpeter”, ≥ 99% pure
Urea fertilizer	Nitrogen 46%

Because the calcium nitrate, sodium nitrate, and urea fertilizers are mixtures, their contents vary considerably by manufacturer. To closely replicate the experimental results using any of the above admixtures or for conducting expedient blast hole repair using the final recommended mixing and procedures, refer to the Hasty Road Repair Expedient Guide to match the intended admixture materials with a similar supplier. Calcium chloride contents (and associated results) vary less by manufacturer, but the size of pellets will influence dissolution time in water.

2.3 Mixing

All mortar mixing followed standard laboratory procedures. The mortars were mixed in a Hobart mixer according to ASTM (2011) Standard C305, with minor modifications. The chemical admixtures were dissolved in the mixing water at 20°C to enable rapid and complete dissolution before the

entire solution was cooled to testing temperature (0, −5, or −10°C). The cement was placed into a dry mixing bowl. The mixer was turned on at low speed and water solution was added. Mixing duration was for 30 seconds. The mixer was stopped, the sides of the bowl were scraped down, and mixing was resumed for 1 minute while the sand was added. The mixer was briefly stopped to once again scrape down the sides (10 seconds) and run for a total of 2.5 minutes.

All concrete mixing also followed standard laboratory procedures. The concrete was mixed in a Gilson 59020 electric powered, 3-ft^3 batch size mixer, according to ASTM (2007) Standard C192, with minor modifications. The chemical admixtures were dissolved in the mixing water at 20°C to enable rapid and complete dissolution before the entire solution was cooled to testing temperature (–5°C). Two containers, each with 0.3 lb water solution, were held out to prevent too high a water-cement ratio (to simulate recommended operational procedures given uncertainties in moisture content of aggregates). The mixer and all utensils were dampened. The mixer was then turned on and all course aggregate added. One-third of the water solution and all fine aggregate were then added. All Portland cement and remaining water solution were then added, mixed for 1 minute, and shut off to observe any concrete sticking to the sides of the mixer. Little sticking was observed. The concrete was then mixed for an additional 1 minute, and a sample was taken to observe the consistency. Mixing was continued while adding both 0.3 lb water solution containers (to achieve desired water-cement ratio given no uncertainties in moisture content of aggregates). Mixing ran for a total of 5 minutes.

2.4 Sample preparation and curing

Each mortar was mixed in cold rooms at a nominal temperature of 0, −5, or −10°C. Immediately after mixing, it was cast into either a 50.8- × 101.6- or 101.6- × 203.2-mm plastic cylindrical mold, tapped with a mallet to ensure consolidation, not capped (to simulate realistic operational procedures), and stored at 0, −5, or −10°C.

During the testing final phase, the concrete was mixed in a cold room at nominal temperature of −5 °C. Immediately after mixing, with four lifts it was cast into 50.8- × 101.6- and 101.6- × 203.2-mm plastic cylindrical molds, tapped with a mallet to ensure consolidation, not capped, and stored at −5°C.

2.5 Material evaluation tests

2.5.1 Set time

The primary method of quantifying mortar or concrete workable time and diggability was determined by finding the initial and final set times. The concrete set time may be influenced by factors such as the type of cement, water-cement ratio, temperature, and the addition of chemical admixtures (Klieger and Lamond 1994). The test monitors the stiffening of fresh concrete as the hydration process proceeds after the initial contact of water and binder material (Mindess and Young 1981). The designated values of initial and final set are arbitrarily set at 500 and 4000 psi, respectively. Initial set is considered to be the point at which fresh concrete has lost its workability, and final set is when the concrete begins to gain strength. As applied to the blast hole repairs, the set time test indicated how much time was available for placing and finishing the material and cleaning equipment, how soon the specialized concrete (as predicted by mortar mix) would gain early strength, when trafficking may begin, and when the concrete could be considered undiggable (allowing for site exfiltration and mission completion). Testing was conducted in accordance with ASTM C403 (2008) with minor modifications, such as the test being conducted at time intervals different than recommended so as to capture the early strength gain information.

2.5.2 Diggability and traffickability

A field-expedient procedure needed to be developed to determine a reasonable estimate for concrete diggability, allowing the end user to determine when site security can withdraw guard around the repair site and have a low risk of the unguarded repaired blast hole being manually excavated and re-emplaced with ordnance. Data were collected throughout the test phases to empirically relate penetration resistance to a manual digging attempt, using the maximum penetration resistance reading (≥ 8000 psi) as the time at which to conduct the field diggability verification test (screwdriver scrape test). A screwdriver was chosen for ease of application, as it is a ubiquitous tool for Army units, and because testing at various concrete strengths demonstrated differences easy to identify visually (see results section).

The RG33L Medium Mine-Protected Vehicle (MMPV) was used to estimate maximum expected trafficking requirements because it is one of the

heaviest vehicles (and has the highest tire-exerted pressure on the road surface) in the Army arsenal and because it is also a candidate for use in current blast hole repair missions. Because the RG33L exerts an effective road-surface pressure of 320 psi when combat loaded (PM-MRAP 2008), initial set (500 psi) was determined a suitable estimate for initial time of trafficability.[1] However, as traffic requirements are lower than diggability requirements and coincide with a site departure, before which point the blast hole has been determined undiggable, traffic requirements can be assumed met prior to diggability requirements.

2.5.3 Workability

All mortar and concrete mixes were observed by visual and tactile means during initial mixing to estimate initial workability on a 1–10 scale (1 = liquid pour, 10 = unworkable/stiff). Because concrete is often mixed under poorly controlled internal and external variables in this application, an attempt was made to produce, in the end, a recipe with a reliable 2–4 rating (fairly watery and almost pourable to easily workable with only a marginal amount of excess water) while adhering to all other requirements.

1 To browse several types of typical MRAPs used by the DoD at the time of this publication to include the RG33L, see http://peocscss.tacom.army.mil/PdMMVS.html.

3 Results and Discussion

3.1 Introduction

All data for admixtures tested individually or in combination during each phase are included in Appendix A, grouped Tables A1 to A3 by the admixture combinations used. Rather than discuss each table in detail, they are summarized in the tables and graphs that follow and referenced, as necessary, in the text below. The various admixtures will be referred to in tables and figures as the following: CC (calcium chloride); CN (calcium nitrate); U (urea fertilizer); NaN (sodium nitrate fertilizer); CCCN *x*%, *y*% (where *x*% is the calcium chloride percentage by weight of the total weight of Type I cement used and *y*% is the calcium nitrate percentage by weight of the total weight of Type I cement used; e.g., CCCN 4%, 15%); and CCU *x*%, *z*% (where *z*% is the urea fertilizer percentage by weight of the total weight of Type I cement used; e.g., CCU 6%, 9%).

3.2 Single admixture scanning phase

As previous studies detail the freezing points of the various admixtures by percent of weight of the cement (Korhonen 1999), initial laboratory testing focused on admixture proportions likely to be at minimum threshold levels required, or higher, to prevent mortar freezing and to act as an accelerator, freezing point depressant, or retarder. The predicted primary effects of the admixtures were observed, as detailed in Table 1 and shown graphically in Figure 1.

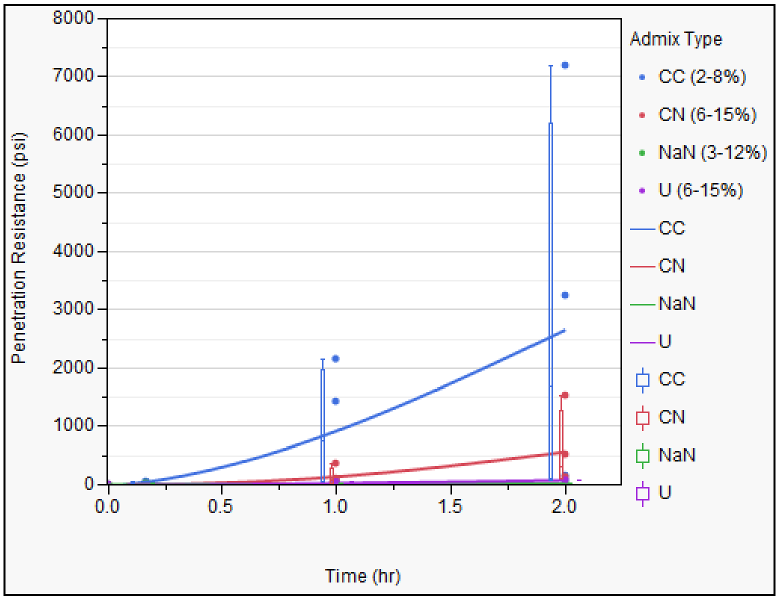

Figure 1. Individual admixture scanning phase results: penetration resistance (psi) vs. time (hr) by admixture type (varying dosage levels as % by weight of cement) at −5°C.

Although calcium chloride acts as both a freezing point depressant and a hydration rate accelerator, its effects depend strongly on the percent by weight of cement used. Figure 1 shows the large variance in points, depending on admixture type. Calcium nitrate was observed to be more "stable" as a strong freezing point depressant, with low hydration rate acceleration when varying percent by weight of cement used. This was determined from two observations: the calcium nitrate penetration resistance variance was 2 hours over all admix proportions (standard deviations σCC: 3362 psi, σCN: 668 psi), and the calcium nitrate depressed the freezing point suitably for all admix proportions used. Sodium nitrate and urea depressed the mortar mix freeze point only for the three highest proportions used. Additionally, calcium chloride acted as a stiffener in the mortar mix, making it less workable at the same water-cement ratio versus the other admixtures, which all presented strong workability properties at w/c 0.36. Based on these results, the following admixture combinations were predicted as the best candidates to produce the intended effects with a lower variance in results by admixture percent weight of cement used: calcium chloride and calcium nitrate; calcium chloride and sodium nitrate; and calcium chloride and urea.

Table 2. Results of laboratory penetration resistance values for candidate admixtures at −5°C nominal temperature.

Admix	Primary effect observed	% of cement by wt admix	Mean room temp °C	Mix #	Penetration Resistance (psi), Individual Admixtures in Mortar Mix — Time (min) 10	60	120	Workability (1–10, 1=liquid pour)	Notes/ observations
Calcium chloride	Accelerant	2	−5.2	1	8	44	70	2	Solid Concrete at 24 hr
		4	−5.3	2	12	78	160	2.5	Solid Concrete at 24 hr
		6	−5.2	3	40	1440	3240	3	Solid Concrete at 24 hr
		8	−5.2	4	22	2150	7200	4	Solid Concrete at 24 hr
Calcium nitrate	Slight accelerant, freeze point depressant	6	−5.1	5	6	70	120	2.5	
		9	−5.1	6	0	100	520	2	
		12	−5.0	7	0	28	110	2	
		15	−5.0	8	2	360	1530	1.5	
Sodium nitrate	Freeze point depressant	3	−5.0	13	36	12	30	2	
		6	−5.1	14	4	8	4	1	did not freeze/form concrete at 24 hr
		9	−5.2	15	4	20	24	1	did not freeze/form concrete at 24 hr
		12	−5.2	16	2	16	20	1	did not freeze/form concrete at 24 hr
Urea	Freeze point depressant	6	−5.3	17	0	64	80	3	some icing; did not freeze/form concrete at 24 hr
		9	−5.7	18	0	52		3	did not freeze/form concrete at 24 hr
		12	−5.8	19	0	0		3	did not freeze/form concrete at 24 hr
		15	−5.8	20	0	0		3	did not freeze/form concrete at 24 hr

3.3 Admixture combination effects phase

Figure 2 shows the results from all of the tests involving CCCN and CCU at a variety of proportions and temperatures compared to CC alone. CCU depresses the water freeze point and retards the cement hydration rate but is not followed by a rapid strength gain within the desired time (3–5 hours). CCU was, therefore, removed from the list of viable candidate admixture combinations. CCCN is shown in the same figure to provide a variety of results at different temperatures and water-cement ratios depending on the admixture proportions.

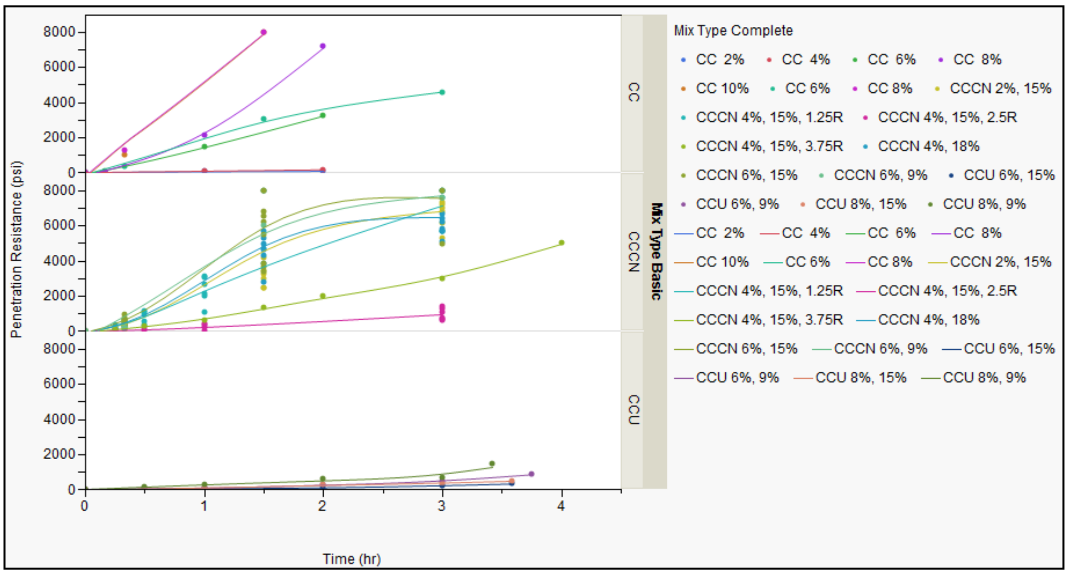

Figure 2. Results of laboratory penetration resistance values for calcium chloride, CCCN, and CCU combinations at −10 to 0°C nominal temperatures using mortar mixes (summary combination effects phase testing compared to phase I calcium chloride results).

Figure 3 shows the results from the best admixture combination identified, CCCN, compared to the effects of calcium chloride used alone. The high variability in strength gain when varying the proportion of calcium chloride in low quantities becomes apparent. CCCN exhibits varying degrees of initial retarding followed by rapid strength gain while simultaneously depressing the freeze point. Other promising signs noted were the reduction in variance between proportion change of admixture when using CCCN and the resulting penetration resistance over time (at 90 minutes, σCC: 2864 psi, σCCCN: 1501 psi). This variance reduction ensures more predictable results for the end user, who, because of operational and equipment restraints, will exhibit much lower precision in all concrete component proportions. It is worth noting that the variance in calcium

chloride results was, in reality, much higher because any entry for 8000 psi is a lower bound for a true reading because of equipment limitations.

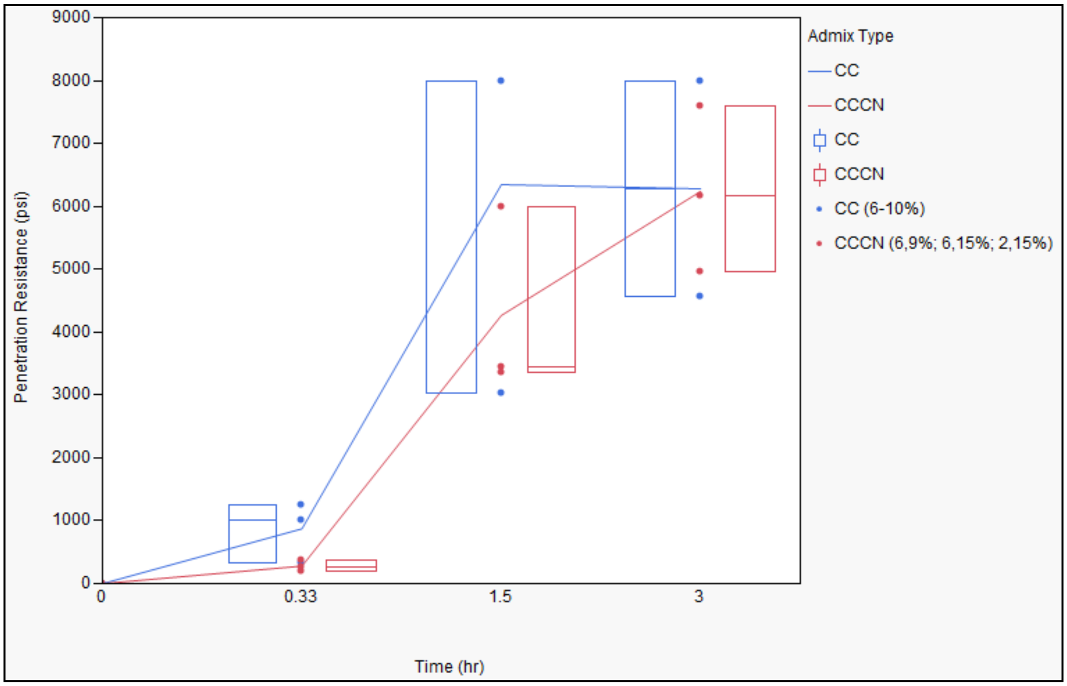

Figure 3. Results of laboratory penetration resistance values for calcium chloride and calcium nitrate combinations (vs. calcium chloride single admixture mixes) at −5°C nominal temperature and w/c 0.36.

Unlike the calcium chloride mixtures, all of the CCCN mixtures demonstrated better results for inducing an initial hydration retarding effect followed by rapid strength gain. Still, none of the CCCN proportions provided a 1–1.5 hour initial retarding effect while still reaching undiggability (≥ 8000 psi) by 3–5 hours at all desired temperature ranges (–10 to 0°C) using a water-cement ratio of 0.36 and concrete component materials proportions (1:2:3). Therefore, it was necessary to obtain a lower bound for a CCCN combination that would provide a longer (but not too long) workability time followed by rapid strength. To achieve this, a slightly lower CC content (4%), higher water-cement ratios, and a commercial retarder (Pozzolith 100 XR) were introduced, as shown in Figure 4. This was effective because higher water-cement ratios and commercial retarders have established properties of slowing concrete's initial hydration rates and strength gains (Ramachandran 1995). Note that all mixes were over 8000 psi 24 hours later for all temperature samples (0, –5, –10°C). Mix 2 provided a suitable lower bound, with a behavior similar to CCU, where temperature was much less an influential factor as the high water content (w/c

0.47) and the commercial retarder in slowing the initial strength gain of the concrete previously seen with all CCCN proportions.

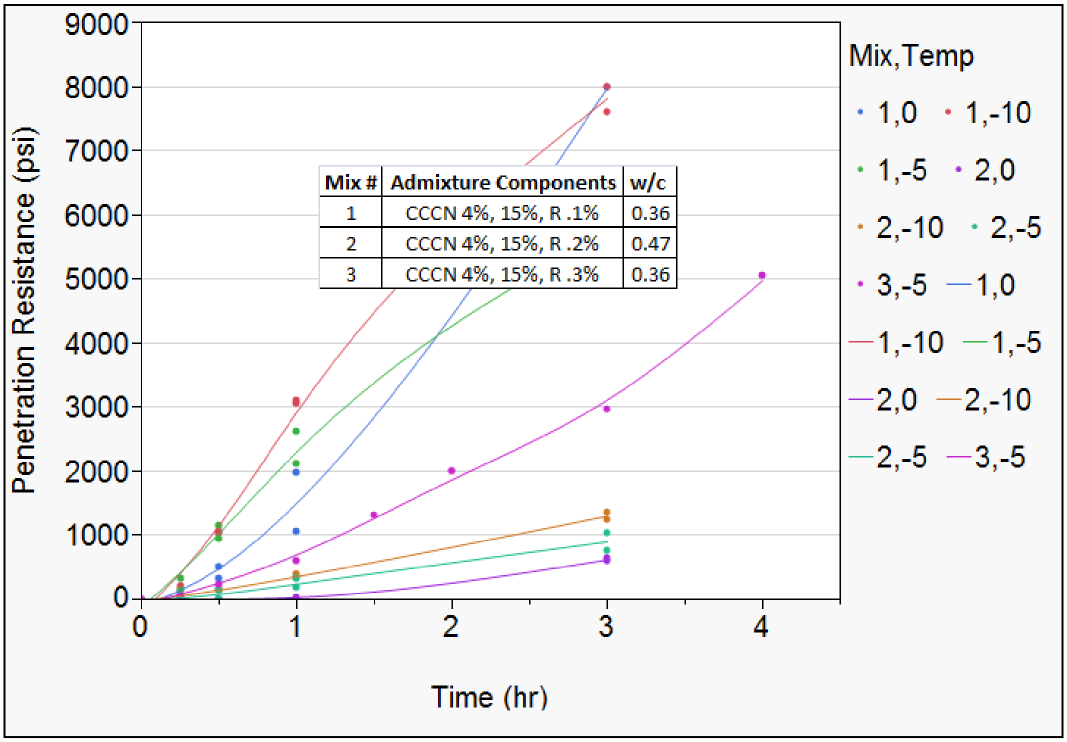

Figure 4. Results of laboratory penetration resistance values for CCCN with commercial retarder Pozzolith 100 XR at 0, −5, −10°C nominal temperatures and varied water-cement ratios (0.36, 0.47).

Because we did not have the resources to conduct at least three tests per independent variable, it is difficult and can be dangerous to infer too heavily from the CCCN results. However, some interesting results are worth noting, all leading to the decision to use CCCN 4%, 15% at w/c 0.40, for a final concrete verification test. First, the only CCCN proportions and water-content ratios (out of eight combinations tested at either 0, −5, or −10°C) that together provided at least 1 hour workable time with a strength gain close to 8000 psi by 3–5 hours was mix 2 from Figure 4. By means analysis, we see that either the water-cement ratio or the commercial retarder (or both) accounts for this change (with caveats: we necessarily assume here that mix 3 has a suitably low variance if repeated where its range of values at 2, 3, and 4 hours for penetration resistance is statistically differentiable from the range of values for mix 1 and mix 2). For other reasons leading to this conclusion, we need to first develop comprehensive models using all the mortar samples data below.

3.4 Evaluating models using all mortar samples data

We fit various step-wise regression models on all mortar samples data using standard statistical software (JMP) to quantify which effects variables exert the greatest influence on our dependent variable as well as to attempt to account for as much variance as possible in our overall models (Table 2).

Table 3. Results of select step-wise regression models with and without two-way interaction terms using all mortar samples testing data and using AIC stopping criterion.

Model #	Data used	input factors	train			test		all data	
			factors chosen (within a = 0.05)	Adj R^2	RMSE	Adj R^2	RMSE	Adj R^2	RMSE
1	1–3 (all)	time;	time;	0.472	1963	0.34	2048	0.443	1983
2	1–3 (all)	time; w/c; retarder; CaCl; CN; urea; NaN; avg temp	time; w/c; CaCl; CN;	0.653	1590	0.525	1737	0.623	1630
3	1–3 (all)	time; time^2; w/c; retarder; CaCl; CN; urea; NaN; avg temp	time; w/c; CaCl; CN;	0.653	1590	0.525	1737	0.623	1630
4	1–3 (all-8000 psi)	time;	time;	0.404	1611	0.439	1317	0.409	1548
5	1–3 (all-8000 psi)	time; w/c; retarder; CaCl; CN; urea; NaN; avg temp	time; w/c; CaCl; CN; avg temp	0.624	1280	0.665	1017	0.623	1236
6	1–3 (all-8000 psi)	time; time^2; w/c; retarder; CaCl; CN; urea; NaN; avg temp	time; time^2; w/c; CaCl; CN; avg temp	0.63	1269	0.686	985	0.633	1220
7	1–3 (all)	time; Mix Type Basic	time; Mix Type Basic (except NaN, CCU)	0.573	1766	0.479	1820	0.554	1774
8	1–3 (all)	time; w/c; retarder; Mix Type Basic; CaCl; CN; urea; NaN; avg temp	Mix Type (except NaN); retarder; avg temp; w/c; time	0.677	1535	0.574	1646	0.653	1565
9	1–3 (all)	time; time^2; w/c; retarder; Mix Type Basic; CaCl; CN; urea; NaN; avg temp	Mix Type (except NaN); retarder; w/c; time	0.677	1535	0.574	1646	0.653	1565
10	1–3 (all-8000 psi)	time; Mix Type Basic	time; Mix Type Basic (except NaN, CCU, CN)	0.515	1453	0.592	1123	0.53	1380

Model #	Data used	input factors	train			test		all data	
			factors chosen (within a = 0.05)	Adj R^2	RMSE	Adj R^2	RMSE	Adj R^2	RMSE
11	1–3 (all-8000 psi)	time; w/c; retarder; Mix Type Basic; CaCl; CN; urea; NaN; avg temp	Mix Type (except NaN); CaCl; retarder; avg temp; w/c; time	0.638	1257	0.709	948	0.643	1202
12	1–3 (all-8000 psi)	time; time^2; w/c; retarder; Mix Type Basic; CaCl; CN; urea; NaN; avg temp	Mix Type (except NaN); CaCl; retarder; avg temp; w/c; time; time^2	0.645	1245	0.736	902	0.653	1186
16	1–3 (all-8000 psi)	time; Mix Type Complete	time; Mix Type Complete (selected)	0.634	1264	0.597	1116	0.62	1242
17	1–3 (all-8000 psi)	time; w/c; Mix Type Complete; avg temp	Mix Type Complete (selected); avg temp; time	0.649	1237	0.633	1065	0.631	1223
18	1–3 (all-8000 psi)	time; w/c; Mix Type Complete; avg temp	Mix Type Complete (selected); avg temp; time; time^2	0.657	1223	0.645	1248	0.643	1204
19	1–3 (all-8000 psi)	time; CaCl; CN; urea; NaN; retarder	CaCl; CN; urea; retarder; time; CCU; CCTime; CNTime; UTime; RetarderTime	0.803	926	0.861	656	0.804	891
20	1–3 (all-8000 psi)	time; w/c; retarder; CaCl; CN; urea; NaN; avg temp	CaCl; CN; urea; retarder; avg temp; w/c; time; CCw/c; CCTime; CNAvgTemp; CNTime; Utime; RetarderTime; w/cTime	0.858	786	0.955	372	0.872	720
21	1–3 (all-8000 psi)	time; time^2; w/c; retarder; CaCl; CN; urea; NaN; avg temp	CaCl; CN; retarder; avg temp; w/c; time; CCw/c; CCTime; CNAvgTemp; CNTime; RetarderTime; w/cTime; Time^2	0.862	775	0.948	400	0.869	729
	model produced insufficient results								
	model produced marginal results								
	best model results								

These results will provide more insight as to our ability to predict how various admixtures, either alone or in combination, may affect penetration resistance over time in future experiments (experiment and results repeatability) that will be subject to various effects such as temperature, water-cement ratio, and other environmental variables. Table 2 summarizes results from various regression models, with and without two-way interaction terms between various components.

A step-wise regression model is used in this case to automatically introduce all combinations of possible effects variables into our models in various order sequences, as each model's results depend on the order in which effects variables are "chosen." When using a step-wise regression method, various stopping rules can be used to determine the optimal mix of effects variables to include in our model. This will help to explain the variance in our dependent variable without "overfitting" our model, such as the minimum Aikake Information Criterion (AIC) or minimum Bayesian Information Criterion (BIC) (Kutner et al. 2005). We use AIC across all models for consistency but note that BIC provides similar results in most of the models in Table 2.

All models in Table 2 are color-coded green, yellow, or red to convey overall efficacy in both prediction ability on a blind data subset (random split: 75% train, 25% test) as measured by the test root mean squared error (RMSE) and in its ability to account for explainable variance as described by the adjusted coefficient of determination (adj. R^2). We first observe that all models that only use simple linear regression terms (e.g., no two-way interactions between various effect variables) can explain, at most, approximately 65% of the data variance (max adj. R^2 0.645), certainly too low to be reliable or meaningful.

Next, we note that, regardless of using two-way interaction terms or linear regression terms, we achieve significantly better model results (prediction and overall explainable variance) when we remove our outlier points: all penetration resistance values greater than 8000 psi. Recall that our penetrometer has a maximum reliable reading of 8000 psi; and during data collection, any readings above maximum were stored as 8000. Discarding these points as outliers dramatically improves our results in all model cases (15–20% RMSE reduction).

Finally, we note that several models produce suitable prediction (RMSE of about 775 psi) and explainable variance results (adj R^2 0.87), using similar effects variables. All three "best" models shared the following effects variables: time, all individual admixture variables (CaCl, CN, urea, retarder), average temperature, CaCl × time, CN × time, and retarder × time. Further, two out of the three best models used w/c × time. These two-way interaction variables (retarder × time or w/c × time in addition to CaCl × time and CN × time) are able to suitably account for the non-linearity in penetration resistance over time seen in our data, an important final step

in obtaining useful model accuracy and precision. Interestingly, no two-way interaction terms were needed between CaCl and CN to account for their interactions over time. These final analyses bolstered our decision to transition from the admixture combination effects phase to final concrete verification test phase using the modified concrete component quantities listed.

We now compare select models' prediction abilities graphically to identify potential problems in various models, such as non-normality in error terms and other undesirable effects. To do this, we use each model's estimates for variables used and coefficient terms to predict penetration resistance on our withheld blind test data subset (as well as record results from train subset). We then order all data by actual penetration resistance observed from lowest to highest, as shown in Figure 5. The vertical distance of each predicted model value to the actual penetration resistance value (blue diamonds) represents the magnitude of each error term, as a prediction will lie directly on the blue diamonds if there were no error. We first observe that the best of our linear regression models (Presist_18) exhibits several problems. To start, this model (and all other linear regressions) fails to account for obvious non-linear effects in various components of our data, shown in the green triangles' linear trend as compared to the non-linear blue diamonds. Next, it performs only marginally well in prediction ability throughout all time regions. Our non-linear (two-way interaction) models perform significantly better in both areas, with model 20 best capturing the overall non-linear trend and shape of our data, as well as providing near-normally distributed error terms with the lowest average error (RMSE). Note that there is evidence of non-normality particularly at the right tail (disproportionately large error terms generally below actual psi values); but these issues occur near or at penetration resistance values of 8000 psi, values which we have already treated as outliers (and can ignore).

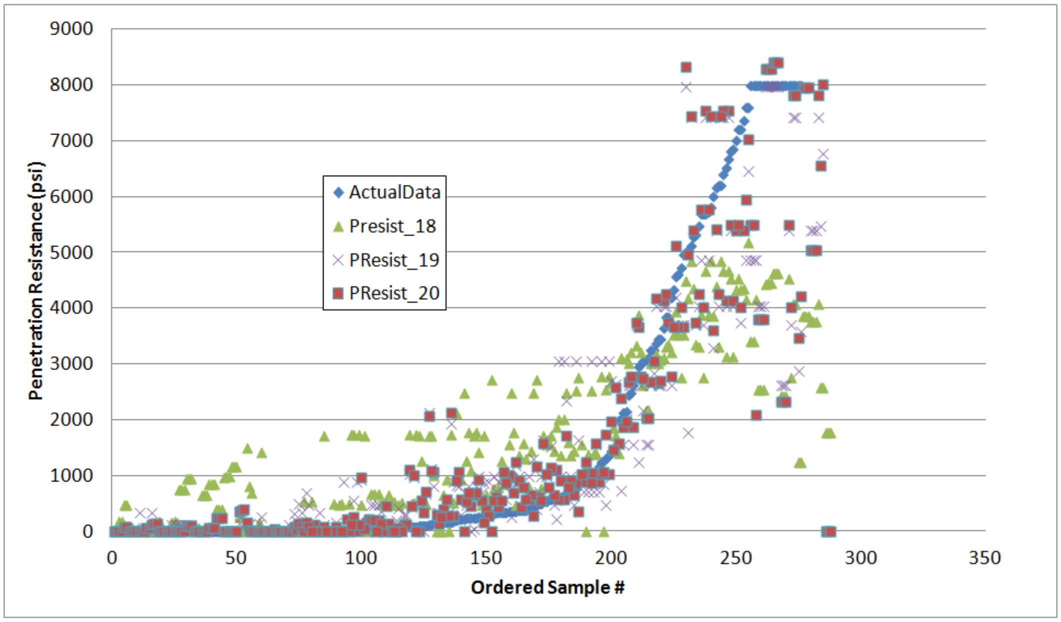

Figure 5. Prediction results (on training and blind data subsets) of select step-wise regression models with and without two-way interaction terms. These use all mortar samples testing data and AIC stopping criterion. Data are ordered from smallest to largest by actual psi observed and plotted as psi versus ordered sample number (0 sample number corresponds to 0 psi actual; 300 sample number corresponds to 8000 psi actual).

3.5 Results verification concrete test

Owing to time and resource limitations, only one concrete test was done using the best admixture candidate and other parameters identified in the admixture combination effects phase. Figure 6 shows the results of the concrete test at −5°C using admixture combination CCCN 4%, 15%, using a concrete materials ratio of 1:2:3 and w/c 0.40. As expected, the admixture combination provided an initial retarding (about 1.5 hours) before initial set followed by a rapid strength gain, while simultaneously depressing the water freeze point. Penetration resistance was projected to reach a maximum penetrometer reading (8000 psi) at 4.5 hours. Because of the addition of course aggregate, the concrete reached the point of undiggability using unpowered equipment by 4 hours after the initial water addition to the cement, as shown by the scrape test and a more persistent digging attempt in Figures 7 and 8. The consistency of the mix given the water-cement ratio was a 3–4 (10 = too dry to be workable; 1 = able to pour).

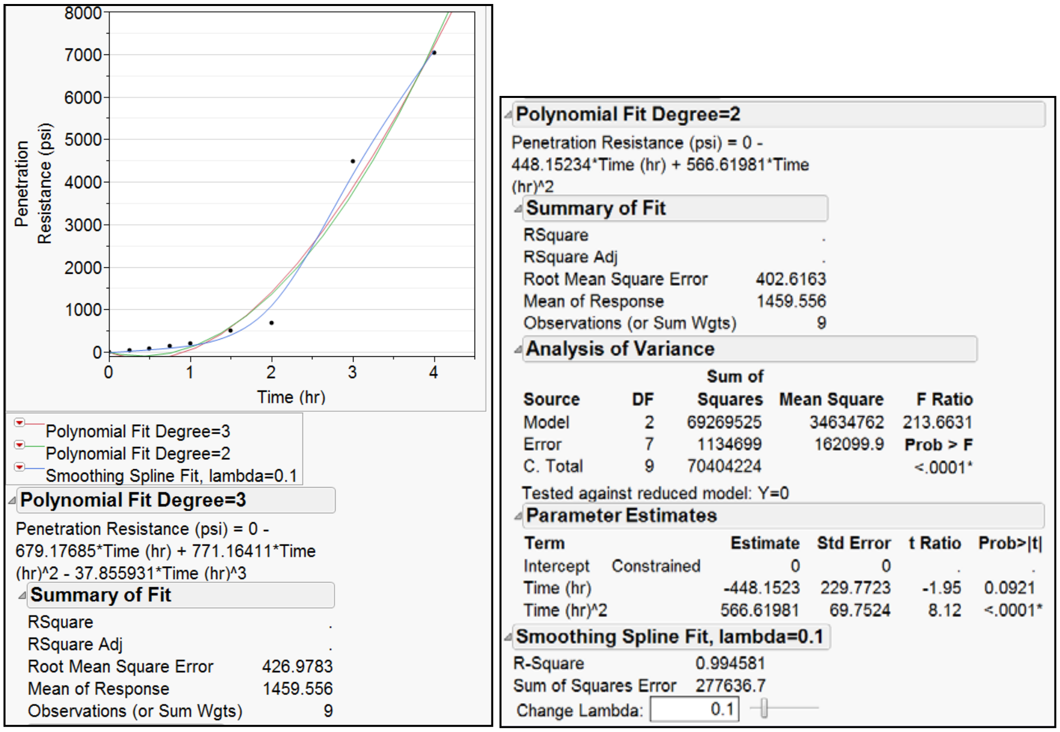

Figure 6. Results of laboratory penetration resistance test for concrete mix using admixture combination CCCN 4%, 15% at -5°C nominal temperature and w/c 0.40.

Additional testing should be conducted to fit a reliable curve over repeated measurements between penetration resistance and time, but several are shown in Figure 6 for observational purposes only. The second order polynomial performs suitably well (RMSE 403 psi vs 427 psi third order polynomial, comparable results to smoothing spline with smoothing constraint $\lambda = 0.1$) within the narrow response range (0–8000) but will likely perform poorly for a variety of input parameters (w/c) and variables (temperature) or outside of this narrow response range.

Figure 7. Scrape test at 4 hours for concrete mix using admixture combination CCCN 4%, 15% at −5°C nominal temperature, and w/c 0.40.

Figure 8. Concrete at 4 hours, shown after 2 minutes of deliberate digging attempt with screw driver for mix using admixture combination CCCN 4%, 15% at −5°C nominal temperature, and w/c 0.40.

4 Conclusions

It has been shown that a combination of admixtures can be used to provide three simultaneous properties necessary for concrete to be initially workable and still rapidly gain strength in low temperatures (−10 to 0°C): an initial retarding (1–1.5 hours) before initial set (500 psi penetration resistance), a rapid strength gain (≥ 8000 psi) by 3–5 hours, and a simultaneous depressing of the water freeze point. Calcium chloride and calcium nitrate fertilizer used together (CCCN 4%, 15%) have most reliably and stably provided this combination of properties as the following most influential factors are varied within certain ranges: temperature (−10 to 0°C), water-cement ratio (target = 0.40), and admixture proportions. An empirical method of verifying final set (screw driver test) has been suggested as an effective means for Army operational units to verify concrete undiggability before removing security and exfiltrating the site Appendix B summarizes this method.

The primary and second-order (interaction) effects of the most influential factors have been quantified for mortar samples as an expedient surrogate for understanding how concrete samples will similarly behave. It has been shown that time, all individual admixture variables (CaCl, CN, urea, retarder), average temperature, CaCl × time, CN × time, and retarder × time are necessary to adequately predict penetration resistance over time. However, as this study focused only on the early strength gains, the findings do not characterize the strength gains over a broader time period. Further, only one concrete sample was collected, the results of which behaved as expected—a delayed strength gain followed by rapid set by 3–5 hours after the initial water introduction—but only at −5°C, at a specific water-cement ratio, and with other controlled conditions. The concrete results need to be verified and understood through repeated testing under the same and additional variations. Therefore, although CCCN has been shown to demonstrate the desired results in a carefully controlled environment under certain conditions, predictions of concrete's early strength behavior under a variety of conditions, other than specified, remains unknown (see recommendations).

5 Recommendations

While CCCN 4%, 15% demonstrated successful results during the final concrete test, there are a number of questions which remain to be answered in depth. The first category of questions involves the explicit characterization and relationship of the various independent variables on the dependent variable, penetration resistance as a function of time for the CCCN admixture combination. Because of time and resource limitations, the test reviewed known significant independent variables and characterized the first and second-order effects of these variables on the dependent variable using mortar as a proxy for concrete sample testing. Several obvious independent variables were carefully controlled and varied through a sequence of testing to arrive at one successful admixture combination for ambient temperature range −10 to 0°C, given other fixed input variable parameters (such as water-cement ratio, concrete component proportions, mixing equipment, and cement type) which would meet the project specifications.

The second category of questions remaining requires a more thorough search of candidate admixtures to answer reliably. While CCCN provides relatively stable results as intended, are there any other candidate materials readily available to Army operational units in Afghanistan which will perform as well, or better, in combination given the same types of independent controllable and uncontrollable variables?

The third category of questions remaining requires a field study to answer effectively. After characterizing carefully controlled independent variables and quantifying their relationship with the dependent variable for concrete samples as outlined above, a number of field tests should be conducted to answer the following questions: What effect do variation of equipment, mixing procedures, and other difficult to control variables (likely to be introduced by operational units in Afghanistan conducting the hasty blast hole repair mission) have on the concrete initial workability time and final undiggable time? One known problem is that the Army Mobile Concrete Vehicle has difficulty mixing the concrete components in precise proportions, including the water-cement ratio. This problem is likely to be exacerbated, due to imprecise weighing or volume estimation, by units using just a mobile mixer and generator and lacking the time and training to es-

timate moisture content of the aggregates. How can this be mitigated? What are the effects of size on hole repairs? What effect do environmental variables such as precipitation (during, before, or after concrete mixing; in the blast hole; and others) have on workability and final undiggable time? What are the best time requirements to use for required initial workability time and final undiggable time? What practical difficulties and limitations will be encountered by these operational units, given a certain type of equipment (The Army's Concrete Mobile Mixer, portable concrete mixer and generator, or other), concrete background and expertise, and other factors? Does the admixture significantly degrade the concrete in the medium term (0.25–1 year) to the point of being untrafficable?

All three categories of questions should be studied in more detail to better understand the relationship of the admixtures to various controllable and uncontrollable factors and to better characterize the results, problems, and solutions likely to be encountered by Army operational units conducting the hasty blast hole repair mission.

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Appendix A: Laboratory Test Data

Table A1. Single Admixture Scanning Phase. Results of laboratory penetration resistance values for candidate admixtures at −5 °C nominal temperature, w/c 0.36, and concrete materials ratio 1:2:3 for all specimens.

Penetration Resistance (psi), Individual Admixtures in Mortar Mix									
					Time (min)				
Admix	Primary Effect Observed	% of cement by wt admix	Mean Room Temp °C	Mix #	10	60	120	Workability (1–10, 1 = liquid pour)	Notes/Observations
Calcium Chloride	Accelerant	2%	−5.2	1	8	44	70	2	Solid Concrete at 24 hr
		4%	−5.3	2	12	78	160	2.5	Solid Concrete at 24 hr
		6%	−5.2	3	40	1440	3240	3	Solid Concrete at 24 hr
		8%	−5.2	4	22	2150	7200	4	Solid Concrete at 24 hr
Calcium Nitrate	Slight Accelerant, Freeze Point Depressant	6%	−5.1	5	6	70	120	2.5	
		9%	−5.1	6	0	100	520	2	
		12%	−5.0	7	0	28	110	2	
		15%	−5.0	8	2	360	1530	1.5	
Sodium Nitrate	Freeze Point Depressant	3%	−5.0	13	36	12	30	2	
		6%	−5.1	14	4	8	4	1	did not freeze/form concrete at 24 hr
		9%	−5.2	15	4	20	24	1	did not freeze/form concrete at 24 hr
		12%	−5.2	16	2	16	20	1	did not freeze/form concrete at 24 hr
Urea	Freeze Point Depressant	6%	−5.3	17	0	64	80	3	some icing; did not freeze/form concrete at 24 hr
		9%	−5.7	18	0	52		3	did not freeze/form concrete at 24 hr
		12%	−5.8	19	0	0		3	did not freeze/form concrete at 24 hr
		15%	−5.8	20	0	0		3	did not freeze/form concrete at 24 hr

Table A2. Admixture Combination Effects Phase. Results of laboratory penetration resistance values for candidate admixtures at specified nominal temperatures (0, −5, or −10°C), water-cement ratios, and mix types (with concrete materials ratio 1:2:3 for all specimens).

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (during test)	Nominal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3D	0.04	0.15	0	1.25	1.1	0	70	0.36	0	0	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	70	0.36	0	0	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	70	0.36	68	0.25	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	70	0.36	68	0.25	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	70	0.36	330	0.5	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	71	0.36	500	0.5	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	71	0.36	1060	1	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	71	0.36	1980	1	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	71	0.36	8000	3	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	1.1	0	71	0.36	8000	3	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	72	0.36	0	0	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	72	0.36	0	0	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	72	0.36	312	0.25	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	72	0.36	148	0.25	CCCN	CCCN 4%, 15%, 1.25R

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (dur-ing test)	Nomi-nal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3D	0.04	0.15	0	1.25	−5.4	−5	72	0.36	1150	0.5	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	73	0.36	950	0.5	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	73	0.36	2620	1	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	73	0.36	2120	1	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	73	0.36	5680	3	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−5.4	−5	73	0.36	5720	3	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	74	0.36	0	0	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	74	0.36	0	0	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	74	0.36	152	0.25	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	74	0.36	216	0.25	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	74	0.36	1030	0.5	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	75	0.36	1050	0.5	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	75	0.36	3060	1	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	75	0.36	3100	1	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	1.25	−9.3	−10	75	0.36	7600	3	CCCN	CCCN 4%, 15%, 1.25R

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (dur-ing test)	Nomi-nal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3D	0.04	0.15	0	1.25	−9.3	−10	75	0.47	8000	3	CCCN	CCCN 4%, 15%, 1.25R
3D	0.04	0.15	0	2.5	1.4	0	76	0.47	0	0	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	76	0.47	0	0	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	76	0.47	0	0.25	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	76	0.47	0	0.25	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	76	0.47	0	0.5	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	77	0.47	4	0.5	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	77	0.47	20	1	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	77	0.47	24	1	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	77	0.47	640	3	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	1.4	0	77	0.47	600	3	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.4	−5	78	0.47	0	0	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.4	−5	78	0.47	0	0	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.4	−5	78	0.47	0	0.25	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.4	−5	78	0.47	0	0.25	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.4	−5	78	0.47	0	0.5	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.5	−5	79	0.47	144	0.5	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.5	−5	79	0.47	180	1	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.5	−5	79	0.47	320	1	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.5	−5	79	0.47	760	3	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−5.5	−5	79	0.47	1040	3	CCCN	CCCN 4%, 15%, 2.5R

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (during test)	Nominal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3D	0.04	0.15	0	2.5	−9.0	−10	80	0.47	0	0	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.0	−10	80	0.47	0	0	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.0	−10	80	0.47	36	0.25	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.0	−10	80	0.47	20	0.25	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.0	−10	80	0.47	160	0.5	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.1	−10	81	0.47	136	0.5	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.1	−10	81	0.47	380	1	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.1	−10	81	0.47	340	1	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.1	−10	81	0.47	1240	3	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	2.5	−9.1	−10	81	0.47	1360	3	CCCN	CCCN 4%, 15%, 2.5R
3D	0.04	0.15	0	3.75	−5.4	−5	82	0.36	0	0	CCCN	CCCN 4%, 15%, 3.75R
3D	0.04	0.15	0	3.75	−5.4	−5	82	0.36	48	0.25	CCCN	CCCN 4%, 15%, 3.75R
3D	0.04	0.15	0	3.75	−5.4	−5	82	0.36	240	0.5	CCCN	CCCN 4%, 15%, 3.75R
3D	0.04	0.15	0	3.75	−5.4	−5	82	0.36	592	1	CCCN	CCCN 4%, 15%, 3.75R
3D	0.04	0.15	0	3.75	−5.4	−5	82	0.36	1300	1.5	CCCN	CCCN 4%, 15%, 3.75R
3D	0.04	0.15	0	3.75	−5.4	−5	82	0.36	2000	2	CCCN	CCCN 4%, 15%, 3.75R
3D	0.04	0.15	0	3.75	−5.4	−5	82	0.36	2960	3	CCCN	CCCN 4%, 15%, 3.75R
3D	0.04	0.15	0	3.75	−5.4	−5	82	0.36	5040	4	CCCN	CCCN 4%, 15%, 3.75R

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (during test)	Nominal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3C	0.06	0	0.09	0	−5	−5	54	0.45	0	0	CCU	CCU 6%, 9%
3C	0.06	0	0.09	0	−5	−5	54	0.45	60	0.5	CCU	CCU 6%, 9%
3C	0.06	0	0.09	0	−5	−5	54	0.45	60	1	CCU	CCU 6%, 9%
3C	0.06	0	0.09	0	−5	−5	54	0.45	280	2	CCU	CCU 6%, 9%
3C	0.06	0	0.09	0	−5	−5	54	0.45	440	3	CCU	CCU 6%, 9%
3C	0.06	0	0.09	0	−5	−5	54	0.45	880	3.75	CCU	CCU 6%, 9%
3C	0.06	0	0.15	0	−5	−5	55	0.45	0	0	CCU	CCU 6%, 15%
3C	0.06	0	0.15	0	−5	−5	55	0.45	44	0.5	CCU	CCU 6%, 15%
3C	0.06	0	0.15	0	−5	−5	55	0.45	52	1	CCU	CCU 6%, 15%
3C	0.06	0	0.15	0	−5	−5	55	0.45	88	2	CCU	CCU 6%, 15%
3C	0.06	0	0.15	0	−5	−5	55	0.45	220	3	CCU	CCU 6%, 15%
3C	0.06	0	0.15	0	−5	−5	55	0.45	320	3.58	CCU	CCU 6%, 15%
3C	0.08	0	0.09	0	−5	−5	56	0.45	0	0	CCU	CCU 8%, 9%
3C	0.08	0	0.09	0	−5	−5	56	0.45	144	0.5	CCU	CCU 8%, 9%
3C	0.08	0	0.09	0	−5	−5	56	0.45	264	1	CCU	CCU 8%, 9%
3C	0.08	0	0.09	0	−5	−5	56	0.45	576	2	CCU	CCU 8%, 9%
3C	0.08	0	0.09	0	−5	−5	56	0.45	640	3	CCU	CCU 8%, 9%
3C	0.08	0	0.09	0	−5	−5	56	0.45	1440	3.42	CCU	CCU 8%, 9%
3C	0.08	0	0.15	0	−5	−5	57	0.45	0	0	CCU	CCU 8%, 15%
3C	0.08	0	0.15	0	−5	−5	57	0.45	32	0.5	CCU	CCU 8%, 15%
3C	0.08	0	0.15	0	−5	−5	57	0.45	92	1	CCU	CCU 8%, 15%
3C	0.08	0	0.15	0	−5	−5	57	0.45	240	2	CCU	CCU 8%, 15%

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (dur-ing test)	Nomi-nal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3C	0.08	0	0.15	0	−5	−5	57	0.45	360	3	CCU	CCU 8%, 15%
3C	0.08	0	0.15	0	−5	−5	57	0.45	480	3.58	CCU	CCU 8%, 15%
3B	0.06	0.15	0	0	2.4	0	27	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.3	0	28	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.4	0	29	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.4	0	27	0.36	500	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.3	0	28	0.36	400	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.4	0	29	0.36	320	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.4	0	27	0.36	8000	1.5	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.3	0	28	0.36	8000	1.5	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.4	0	29	0.36	8000	1.5	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.4	0	27	0.36		3	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.3	0	28	0.36		3	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	2.4	0	29	0.36		3	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.6	−5	30	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.7	−5	31	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.7	−5	32	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.6	−5	30	0.36	660	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.7	−5	31	0.36	600	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.7	−5	32	0.36	370	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.6	−5	30	0.36	3640	1.5	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.7	−5	31	0.36	6520	1.5	CCCN	CCCN 6%, 15%

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (during test)	Nominal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3B	0.06	0.15	0	0	−5.7	−5	32	0.36	6840	1.5	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.6	−5	30	0.36	8000	3	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.7	−5	31	0.36	8000	3	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−5.7	−5	32	0.36	8000	3	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.2	−10	33	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.3	−10	34	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.3	−10	35	0.36	0	0	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.2	−10	33	0.36	354	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.3	−10	34	0.36	940	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.3	−10	35	0.36	530	0.33	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.2	−10	33	0.36	3840	1.5	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.3	−10	34	0.36	6200	1.5	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.3	−10	35	0.36	5480	1.5	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.2	−10	33	0.36	8000	3	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.3	−10	34	0.36	8000	3	CCCN	CCCN 6%, 15%
3B	0.06	0.15	0	0	−8.3	−10	35	0.36	8000	3	CCCN	CCCN 6%, 15%
3B	0.02	0.15	0	0	2.4	0	36	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	37	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	38	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	36	0.36	40	0.33	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	37	0.36	36	0.33	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	38	0.36	36	0.33	CCCN	CCCN 2%, 15%

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (dur-ing test)	Nomi-nal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3B	0.02	0.15	0	0	2.4	0	36	0.36	8000	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	37	0.36	8000	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	38	0.36	8000	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	36	0.36		3	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	37	0.36		3	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	2.4	0	38	0.36		3	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.6	−5	39	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.7	−5	40	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.7	−5	41	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.6	−5	39	0.36	230	0.33	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.7	−5	40	0.36	90	0.33	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.7	−5	41	0.36	340	0.33	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.6	−5	39	0.36	3440	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.7	−5	40	0.36	3240	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.7	−5	41	0.36	2440	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.6	−5	39	0.36	7000	3	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.7	−5	40	0.36	7360	3	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−5.7	−5	41	0.36	5280	3	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	42	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	43	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	44	0.36	0	0	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	42	0.36	580	0.33	CCCN	CCCN 2%, 15%

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (during test)	Nominal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3B	0.02	0.15	0	0	−8.2	−10	43	0.36	750	0.33	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	44	0.36	410	0.33	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	42	0.36	3000	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	43	0.36	4200	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	44	0.36	2480	1.5	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	42	0.36	6800	3	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	43	0.36	8000	3	CCCN	CCCN 2%, 15%
3B	0.02	0.15	0	0	−8.2	−10	44	0.36	7200	3	CCCN	CCCN 2%, 15%
3B	0.04	0.18	0	0	2.4	0	45	0.36	0	0	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	46	0.36	0	0	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	47	0.36	0	0	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	45	0.36	210	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	46	0.36	340	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	47	0.36	130	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	45	0.36	5680	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	46	0.36	8000	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	47	0.36	4720	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	45	0.36	8000	3	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	46	0.36		3	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	2.4	0	47	0.36	8000	3	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.6	−5	48	0.36	0	0	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.7	−5	49	0.36	0	0	CCCN	CCCN 4%, 18%

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (during test)	Nominal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3B	0.04	0.18	0	0	−5.7	−5	50	0.36	0	0	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.6	−5	48	0.36	380	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.7	−5	49	0.36	650	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.7	−5	50	0.36	560	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.6	−5	48	0.36	2760	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.7	−5	49	0.36	5320	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.7	−5	50	0.36	3840	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.6	−5	48	0.36	5680	3	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.7	−5	49	0.36	6680	3	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−5.7	−5	50	0.36	6400	3	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	51	0.36	0	0	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	52	0.36	0	0	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	53	0.36	0	0	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	51	0.36	240	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	52	0.36	360	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	53	0.36	230	0.33	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	51	0.36	4960	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	52	0.36	4600	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	53	0.36	4320	1.5	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	51	0.36	5800	3	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	52	0.36	6200	3	CCCN	CCCN 4%, 18%
3B	0.04	0.18	0	0	−8.2	−10	53	0.36	5120	3	CCCN	CCCN 4%, 18%

Test	CaCl %	CN %	Urea %	Re-tarder (g)	Avg Temp C (dur-ing test)	Nomi-nal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)	Mix Type Basic	Mix Type Complete
3A	0.06	0	0	0	−6.3	−5	21	CC	0	0	CC	CC 6%
3A	0.06	0	0	0	−6.3	−5	21	CC	340	0.33	CC	CC 6%
3A	0.06	0	0	0	−6.3	−5	21	CC	3040	1.5	CC	CC 6%
3A	0.06	0	0	0	−6.3	−5	21	CC	4560	3	CC	CC 6%
3A	0.08	0	0	0	−6.3	−5	22	CC	0	0	CC	CC 8%
3A	0.08	0	0	0	−6.3	−5	22	CC	1260	0.33	CC	CC 8%
3A	0.08	0	0	0	−6.3	−5	22	CC	8000	1.5	CC	CC 8%
3A	0.08	0	0	0	−6.3	−5	22	CC		3	CC	CC 8%
3A	0.1	0	0	0	−6.3	−5	23	CC	0	0	CC	CC 10%
3A	0.1	0	0	0	−6.3	−5	23	CC	1020	0.33	CC	CC 10%
3A	0.1	0	0	0	−6.3	−5	23	CC	8000	1.5	CC	CC 10%
3A	0.1	0	0	0	−6.3	−5	23	CC		3	CC	CC 10%
3A	0.06	0.09	0	0	−6.3	−5	24	CCCN	0	0	CCCN	CCCN 6%, 9%
3A	0.06	0.09	0	0	−6.3	−5	24	CCCN	200	0.33	CCCN	CCCN 6%, 9%
3A	0.06	0.09	0	0	−6.3	−5	24	CCCN	6000	1.5	CCCN	CCCN 6%, 9%
3A	0.06	0.09	0	0	−6.3	−5	24	CCCN	7600	3	CCCN	CCCN 6%, 9%
3A	0.06	0.15	0	0	−6.3	−5	25	CCCN	0	0	CCCN	CCCN 6%, 15%
3A	0.06	0.15	0	0	−6.3	−5	25	CCCN	260	0.33	CCCN	CCCN 6%, 15%
3A	0.06	0.15	0	0	−6.3	−5	25	CCCN	3360	1.5	CCCN	CCCN 6%, 15%
3A	0.06	0.15	0	0	−6.3	−5	25	CCCN	4960	3	CCCN	CCCN 6%, 15%
3A	0.02	0.15	0	0	−6.3	−5	26	CCCN	0	0	CCCN	CCCN 2%, 15%
3A	0.02	0.15	0	0	−6.3	−5	26	CCCN	380	0.33	CCCN	CCCN 2%, 15%
3A	0.02	0.15	0	0	−6.3	−5	26	CCCN	3440	1.5	CCCN	CCCN 2%, 15%
3A	0.02	0.15	0	0	−6.3	−5	26	CCCN	6160	3	CCCN	CCCN 2%, 15%

Table A3. Concrete verification test phase. Results of laboratory penetration resistance values for concrete mix at nominal temperature −5°C using CCCN 4%, 15%, w/c .40, and concrete materials ratio 1:2:3.

CaCl %	CN %	Avg Temp C (during test)	Mix	Nominal Temp C	Mix #	w/c	Penetration Resistance (psi)	Time (hr)
0.04	0.15	−9.5	1	−10	83	0.4	0	0
0.04	0.15	−9.5	1	−10	83	0.4	32	0.25
0.04	0.15	−9.5	1	−10	83	0.4	72	0.5
0.04	0.15	−9.5	1	−10	83	0.4	144	0.75
0.04	0.15	−9.5	1	−10	83	0.4	192	1
0.04	0.15	−9.5	1	−10	83	0.4	496	1.5
0.04	0.15	−9.5	1	−10	83	0.4	680	2
0.04	0.15	−9.5	1	−10	83	0.4	4480	3
0.04	0.15	−9.5	1	−10	83	0.4	7040	4

Appendix B: Hasty Road Repair Soldier's Expedient Guide

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Problem Definition

In conflict areas in Afghanistan, insurgents are using existing blast holes to plant new IEDs to target coalition convoys. An effective solution to this problem is to repair the blast holes with Portland cement concrete (PCC) materials. During the winter season, insurgent activity diminishes because of cold weather and typically resumes in a spring offensive. It would be desirable to continue the repair of existing blast holes during the winter season to improve security conditions for coalition military convoys maneuvering during the spring offensive. However, normal PCC does not set fast enough in cold environments; and freezing of fresh concrete may permanently damage the PCC material, rendering it ineffective.

The solutions presented, if followed correctly, reduce the required on-site time for Soldiers conducting hasty blast hole repair, and for on-site security, from days currently (depending on temperature and other factors) to approximately 3–5 hours, which is the total amount of time required for the cold weather concrete to harden and set to the point of being non-diggable. This time period begins when water is first added to the cement.

The solutions hereby provided are to be used only for the stated purpose: expedient filling of blast holes in forward military areas in Afghanistan. Do not use these solutions for civilian construction because the material produced may not meet the required quality, durability, and appearance normally required by most architectural and structural applications. For such applications, contact the author for more appropriate solutions.

Effective Solutions

Solution 1: Traditional cold weather concrete method (normally this is not a useful solution for this application)

This is the most common method used in peacetime winter concrete construction but not the best solution for our scenario. The method consists of building an enclosure over the area and using space heaters to create an artificial warm environment during placement and curing of fresh concrete.

Solution 2: Use of accelerating admixtures (use this solution for air temperatures between 41 and 60°F)

Some chemicals, such as calcium chloride, can accelerate the rate of setting and strength development in concrete. Calcium chloride is the most effective accelerating admixture for concrete mixtures. Because calcium chloride has many uses, it is commonly available in bulk and in convenient packages at relatively low prices. It is used as a deicer for roads, as a desiccant, and to control dust at construction sites and on some unpaved roads.

As an accelerating admixture in concrete, you can use between 1 and 2% of calcium chloride by weight of cement. For example, if your batch of concrete requires 100 lbs of cement, you can use 1 lb for moderate acceleration or 2 lb for fast acceleration. Adding more than 2% carries a very high risk of flash set (concrete setting within a few minutes), particularly at these temperatures. A flash set will result in air gaps; but more importantly in this application, it will ruin your equipment before you can clean it and will set the concrete before you have time to spread it over the blast hole or other area.

Calcium chloride is most commonly sold in small bags of dried pellets. First, you need to weigh out the required amount of water or obtain the required water volume (see accompanying Excel calculator). Then, add the

dry calcium chloride to the water and stir, making sure you fully dissolve the admixture. This solution can be prepared days prior to the mission, if necessary, to save valuable time at the mission site, and stored outside at temperatures down to about 20°F without freezing. Once at the mission site, add the calcium chloride solution to the aggregates in the mixing drum. Portland cement is the last material that is added gradually to the mixture. If the calcium chloride is NOT dissolved into the water first, the concrete setting time will be unpredictable, risk large cracks and weakening, and cause other unintended effects.

Calcium chloride is normally not recommended for use with reinforced concrete because it can cause corrosion of steel reinforcement. However, the corrosion problem develops slowly with time; therefore, this problem has a much lower impact in field military applications. Blast hole repairs do not normally contain steel reinforcement, and, therefore, corrosion is not a concern.

Solution 3: Using expedient accelerating and antifreeze admixtures (use this solution for air temperatures between 10 and 40°F)

Antifreeze admixtures are similar to accelerating admixtures. They accelerate the rate of cement hydration and prevent the mixture water solution from freezing. The fresh concrete can be cold and still set well and gain strength rapidly. There are several commercial formulas of antifreeze admixtures for concrete. For this application, calcium nitrate (chemical formula Ca(NO3)2) works well paired with the accelerant calcium chloride (deicer, see the “Solution 2” section). Calcium nitrate (Fig. B1) is most commonly used as a fertilizer, and sometimes it is called Norwegian Saltpeter. Calcium nitrate fertilizer is a fairly standardized product in pellet or flake form (look for ingredients on the bag to say something like “15.5-0-0 + 19% Ca”).

Figure B1. Calcium chloride deicing pellets (left) and calcium nitrate fertilizer (right).

Important note: The proper quantities of calcium chloride, calcium nitrate, and the water-to-cement ratio are critical to the concrete's remaining workable for approximately 30 minutes AND setting rapidly to the point of being non-diggable at 2–4 hours after adding water. Use the appendix Excel calculator or the following to prepare the materials proportionally.

You will have to calculate the proportional weights for the size of your mixture base on the following proportions for 1 yd^3 of concrete:

Portland cement...655 lb/7.0 bags

Water (w/c UP TO .40)..200 lb/24.0 gal*

Coarse aggregate (crushed stone).......................................1966 lb/4 yd^3

Sand...1311 lb/3 yd^3

Calcium Chloride pellets (at 4% weight cement)...........................26.2 lb

Calcium Nitrate fertilizer pellets (at 15% weight cement).............98.3 lb

* assumes 3.0% moisture content in sand and 1.0% moisture content in coarse aggregate. See Excel calculator for adjustments if this is far from actual field conditions.

Coordinate with your unit supply to obtain the admixtures (see Procurement section), and note that local fertilizer (if using calcium nitrate fertilizer) should work just as well.

Mixing instructions: First, you need to weigh out the required amount of water or obtain the required water volume (see accompanying Excel calculator). Then, add calcium chloride at 4% of the intended cement weight

AND add calcium nitrate at 15% of the intended cement weight to warm (but not hot) water and stir, fully dissolving the admixtures. Note that the admixtures will dissolve much more quickly in warmer water and that it is imperative that all the admixtures fully dissolve into the water. This solution can be prepared days prior to the mission, if necessary, to save valuable time at the mission site. It can also be stored outside at temperatures down to about 10°F without freezing. Weigh out and separate 10% of your water solution into one or two separate containers.

Once on mission site, add the water solution (except for the 10% you separated) to the aggregates in the mixing drum. Portland cement is the last material that is gradually added to the mixture. If the calcium chloride and calcium nitrate are NOT dissolved into the water first, the concrete setting time will be unpredictable, risk large cracks and weakening, and cause other unintended effects.

Mix for about 5–8 minutes or until you see a good mixture. Add a portion of the remaining 10% of water only if the concrete is too dry to be workable, and do so incrementally. Note in Figure B2 that our concrete is wet and workable but not liquid. Use without delay. Always suspect that the mixture may harden faster than expected. Add plenty of water to all of your equipment and tools, and mix thoroughly. This will prevent the concrete from setting before you have time to fully clean your equipment back on base.

Figure B2. Concrete mix with calcium chloride and calcium nitrate 5 minutes after introducing water.

To determine when concrete is non-diggable, use a rule of thumb called the “scrape test”. After the concrete has been setting for at least 3 hours AND appears dry to the touch, using a screwdriver, apply pressure and at-

tempt to scrape and dig into the surface (Fig. B3). A minor scarring of the surface with the screwdriver but inability to penetrate the concrete corresponds to a concrete strength gain sufficiently difficult to manually dig a hole in the concrete.

Figure B3. Scrape test for determining when "non-diggable."

Table B1. Cold weather concrete quick reference table

Temperature °F (°C)	Recommended Concrete Admixtures (% by weight of cement used)
> 60 °F (16 °C)	No admixtures required (normal summer procedures)
51 to 60 °F (11 to 15°C)	Calcium Chloride 1%
41 to 50 °F (5 to 10 °C)	Calcium Chloride 2%
10 to 40 °F (−12 to 4 °C)	Calcium Chloride 4% AND Calcium Nitrate Fertilizer 15% Note: use w/c 0.36-0.40 (by weight)

Tips

1. Always run a test mix at a convenient location at the base or camp. Minor mix adjustments may be needed to produce an effective mixture before going to work at areas with risk of hostility.
2. To prepare blast holes, follow procedures in the "Route Remediation Handbook: Repairing Improvised Explosive Device Craters" (easily obtained from the Engineer Branch at the Maneuver Support Center of Excellence, Ft. Leonard Wood, MO). Key tasks will include identifying the extent of upheaved pavement and marking boundaries (Fig. B4); cleaning out and 'squaring off' the blast hole with a jackhammer or skid steer with hammer attachment (Fig. B5); removing all debris and cleaning the substrate and edges from ice, snow, or standing water; and

filling the hole with gravel or other fill material (local material if gravel unavailable) UP TO about 6–9 inches below surface, making sure to compact non-gravel materials. Fill the remaining 6–9 in. depth with the appropriate concrete mix. A 9-in. depth is preferred, but 6 in. is also suitable for larger holes if the blast hole is prepared correctly.

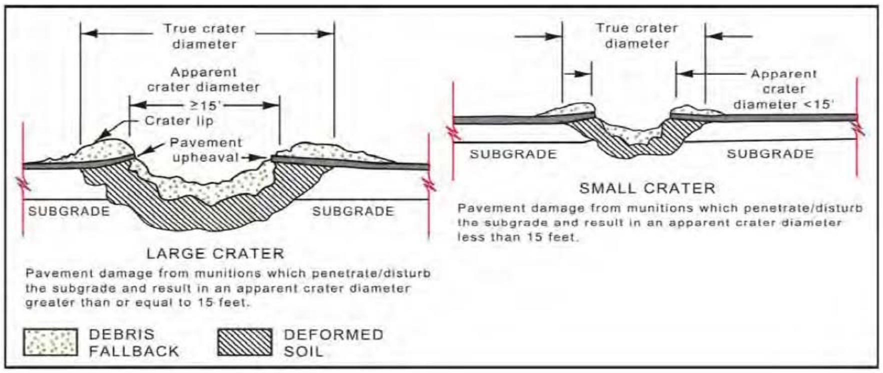

Figure B4. Typical crater terminology. (Image from *ERDC Route Remediation Handbook*.)

Figure B5. Prepared crater ready for backfill. (Image from *ERDC Route Remediation Handbook*.)

3. Avoid placing accelerating or antifreeze concrete when the air temperature is below 10°F. Use the solution appropriate to your air temperature conditions. If the air and concrete materials' temperatures differ, enter these separately in the Excel tool, which will automatically calculate the appropriate admixtures.
4. Accelerating admixtures work well only in air temperatures of 41–60°F. Above these temperatures, accelerating admixtures, even in small quantities, can flash set the concrete. For temperatures of 10–40°F, use the appropriate antifreeze admixture solution as shown above.

5. If the temperature of the concrete materials is much different than the temperature at the intended mix site, use an average of the two temperatures to determine which type of concrete and admixtures to use.

Procurement

Calcium Chloride de-icing pellets:

Major Supply Corp
http://majorsupply.com
888.614.6584
Product info:
“Peladow Calcium Chloride 50 lb bag”
SKU YDOW
Price: $17.75

Simply Solutions
www.simplysolutionsinc.com
888.400.7003
Product info:
“Excel 50 Calcium Chloride Ice Melter 50 lb Bag”
SKU 2143429
Price: $25.50

Global Industrial
www.globalindustrial.com
Product info:
“Bare Ground Granular Ice Melt with CACL Pellets 50 lb Bag”
SKU T9F640162
Price: $13.25

Calcium Nitrate Fertilizer Pellets:

Atlantis Hydroponics
www.atlantishydroponics.com
888.305.4450
Product info: “Calcium Nitrate, 5 lb”
SKU SAI01405
Price: $7.99

Clan Orchids
www.clanorchids.com/store/osgcn.html
941.351.2483
clanlady@clanorchids.com
Product info:
“Calcium Nitrate 15.5-0-0-19 5 lb bag”
SKU osgcn
Price: $13.95

Amazon
www.amazon.com
Product info: “Calcium Nitrate 15.5-0-0-19 5 lb bag”
Price $16.95

Hasty Crater Repair Calculator

Instructions:
Use this calculator as a planning guide for your concrete mix when filling craters with concrete in cold or warm temperatures.
Note that this calculator provides instruction for using admixtures which will speed up total concrete setting time to ~2-5 hours even in cold temperatures do
Do NOT use this calculator or the admixtures listed in order to place concrete intended for structural purposes.
Key inputs: enter required information into all boxes highlighted yellow. Do not change other areas (hidden or not hidden).
Follow the instructions and the notes attached to each input area.
contact for questions:
Jared Oren, US Army Corps of Engineers, ERDC-CRREL
jared.i.oren@usace.army.mil or jared.oren@usace.army.smil.mil

Temperature estimate for the repair site:
14 ° F
Temperature estimate for the materials:
35 ° F
Amount of Desired Concrete (below), or specify the area of the hole to fill (right). Note: make sure one of the cells is blank!
1 yd^3 concrete desired | ft^2 hole size to fill
% moisture content by weight in fine aggregate (sand):
3.0% | 26.2 lb water avail
% moisture content by weight in course aggregate:
1.0% | 9.8 lb water avail

Concrete Mix Materials Required:

Note: Use either the weight or the volume estimate for each material below, whichever is easier depending on desired concrete batch size.

Materials:	weight estimate:		volume estimate:	
Cement	655.33	lb/1yd^3	7.0	bags type 1 or type 1A Portland Cement
Water	199.88	lb/1yd^3	24.0	gallons
Fine Aggregate (Sand)	1310.66	lb/1yd^3	0.3	yd^3
Course Aggregate	1966.00	lb/1yd^3	0.4	yd^3
Admixtures to use:				
Calcium Chloride 4%	26.21	lb/1yd^3		
Calcium Nitrate 15%	98.30	lb/1yd^3		

Note: hold out 10% of total wat (20 lb or 2.4 gallons) as instructed in the Hasty Crater Repair Guide during initial batching.
Add half of this remaining wat (10 lb or 1.2 gallons) only if the concrete is too dry to be workable. Add remaining water if necessary to make workable.
Caution: concrete will take HOURS longer to set / harden to the point of being un-diggable if you have too much water! (more than w/c ~.40)

Calcium Chloride is in the form of bulk deicer pellets.
Calcium nitrate is in the form of bulk fertilizer pellets.
Concrete should be consistency similar to above (NOT too liquid!)

Figure B6. Hasty crater repair calculator screenshot.

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13. SUPPLEMENTARY NOTES

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14. ABSTRACT

Previous research has demonstrated the efficacy of various commercial admixtures for rapid setting concrete in cold weather environments, but this research has mostly focused on gathering data on too large a time window (more than 7 days) and focuses on admixtures largely unavailable in Afghanistan. The research included in this report investigates admixtures which can satisfy the Army operational requirement. These requirements include 45–90 minutes of concrete workability, followed by a rapid-strength gain to the point of being "undiggable," and the ability to support anticipated vehicle loads within 3 to 5 total hours from first contact of water to binder material. This research ignores typical concerns such as long-term durability, aesthetics, corrosion, and others that are of minimal importance in this expedient field use application—concrete not expected to last more than 5 years. Results from this study were incorporated into Army guidance addressing the use of rapid setting materials for crater repair. This report describes the repair methods and early strength gain performance (as measured by penetration resistance) of the rapid setting materials used in laboratory tests to repair small-to-large craters at ambient temperatures (about −10 to 0°C). An appendix then combines this research and existing knowledge of admixture use at temperatures above 0°C to provide non-technical, expedient instructions for Soldiers' tactical hasty road repair in a broad range of low temperatures using locally procurable (in Afghanistan) materials.

15. SUBJECT TERMS

Admixture	Cold regions	IED
Blast hole	Concrete	Repair
	Freezing	

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